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Direct observations of sea-ice thickness and brine rejection off Sakhalin in the Sea of Okhotsk

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ABSTRACT

From December to June 2002–2003, sea-ice and oceanic data were obtained from moorings near Sakhalin in the west central Okhotsk Sea. Ice draft measured by sonar reveals distinct periods of thin and thick ice. Thin-ice periods in January–March corresponded to offshore ice movement and increasing seawater salinity. The measured change in salinity corresponds well with that derived from heat-flux calculations using the observed ice thickness. Brine rejection from ice growing in a coastal polynya off northern Sakhalin is responsible for much of the observed salinity increase. The simultaneous observation of dense shelf water ($>26.7\sigma_{\theta}$) suggests that this region is one possible source. The periods of thick-ice incursion are likely indicative of heavily deformed pack formed further north and drifting south with the current. The mean draft (1.95 m), thick-ice ratio, and keel frequency during these periods are close to values observed in the Beaufort Sea. Freshwater transport estimated from the observed ice thickness and velocity is larger than that of the Amur River discharge.

1. Introduction

The Sea of Okhotsk (Fig. 1) is located downwind of the coldest region in Eurasia and the southernmost sizable sea-ice area in the Northern Hemisphere. Sea-ice production is fairly active within coastal polynyas in the northern part. Brine rejection associated with ice production plays an important role for the formation of dense shelf water (DSW), which is the heaviest water mass originating at the surface in the North Pacific region and a ventilation source of North Pacific Intermediate Water (Talley, 1991; Yasuda, 1997). Since sea ice is mainly produced in the northern part and advected to the southern part, where it melts, it is important for negative heat and positive freshwater fluxes towards the south.

In the Sea of Okhotsk, there have been direct time series observations of currents and water properties in the northwest shelf polynya (Shcherbina et al., 2003, 2004a), which is considered to be a main DSW formation site (Martin et al., 1998; Gladyshev et al., 2000; Ohshima et al., 2003), and across the DSW pathway off northern Sakhalin (Fukamachi et al., 2004). However, there is no available dataset of ice thickness in the northern part, where ice forms most actively. Birch et al. (2000) and Marko (2003) conducted mooring observations with ice-profiling sonars (IPSs) off northern Sakhalin during the winters of 1996–1998. These were the first IPS observations in this sea but a full description of the data and results is not available. In fact, ice-thickness observations are fairly limited and most of them were carried out in the southwestern part. For example, Toyota et al. (2004) surveyed ice off Hokkaido during 1996–2004 using a ship-mounted downward-looking video camera to measure the thickness of floes on edge by the ship's movement. Fukamachi et al. (2003, 2006) conducted moored IPS observations near Hokkaido during the winters of 1999–2001. They showed the average thickness (0.71 m) during these winters and the dominance of the deformed ice in this region.

In this paper, sea-ice characteristics in the northern part of the pathway from the north to south are discussed based on the time series data for the first time. The region of the observation is also within the occasional Sakhalin polynya, which is possible DSW formation site. Sea-ice and oceanic time series data were obtained simultaneously. (To date, the similar dataset of ice and ocean has been obtained only by Drucker et al., 2003 in the St. Lawrence

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Island polynya.) Thus, the obtained dataset is suited not only to examine polynya processes, but to evaluate the importance of this polynya for DSW formation.

2. Data and processing

Two moorings were deployed on 27 December 2002 about 18 km off northern Sakhalin (52°43′N, 143°34′E), where the water depths are 32–33 m (red circle in Fig. 1). They were recovered on 12 June 2003. One mooring contained an IPS (ASL Environmental Sciences IPS4 420 kHz), and another contained an ADCP (RD Instruments WH-Sentinel 300 kHz) and a conductivity-temperature (CT) recorder (SeaBird SBE-37). These two moorings were deployed separately (~120 m apart) to avoid possible acoustic interference. All three instruments were placed at 24-m depth. The IPS sampling intervals were 1 s for range data and 30 s for pressure and tilt data. The ADCP measured ice velocity using the bottom-tracking mode as well as water-column velocity using the water-tracking mode (Melling et al., 1995). Its sampling interval was 20 min and the bin size for water-column velocity was 2 m. Atmospheric pressure data used to process the IPS data and surface-wind data used to process the ADCP data were measured by an automatic weather station in Chaivo (green circle in Fig. 1).

The methods of data processing in this study essentially follow previous work in the Beaufort Sea (Melling and Riedel, 1995, 1996) and the Sea of Okhotsk (Fukamachi et al., 2003, 2006). General discussions on the IPS data processing are found in Melling et al. (1995) and Strass (1998), and details are not provided here. The ice-velocity data are used to convert the draft time series into a pseudo-spatial series. For this purpose, a continuous time series of ice velocity is necessary to estimate the width of the ice-free areas and therefore ice concentration. To estimate ice velocity within data gaps, a multi-linear regression of ice velocity against near-surface water velocity from the uppermost ADCP bin (5–7 m deep) and surface wind measured in Chaivo was performed. The draft data discussed in the following section are the pseudo-spatial series re-sampled to equal along-track spatial increments of 0.5 m. Values are typically accurate within ±0.05 m.

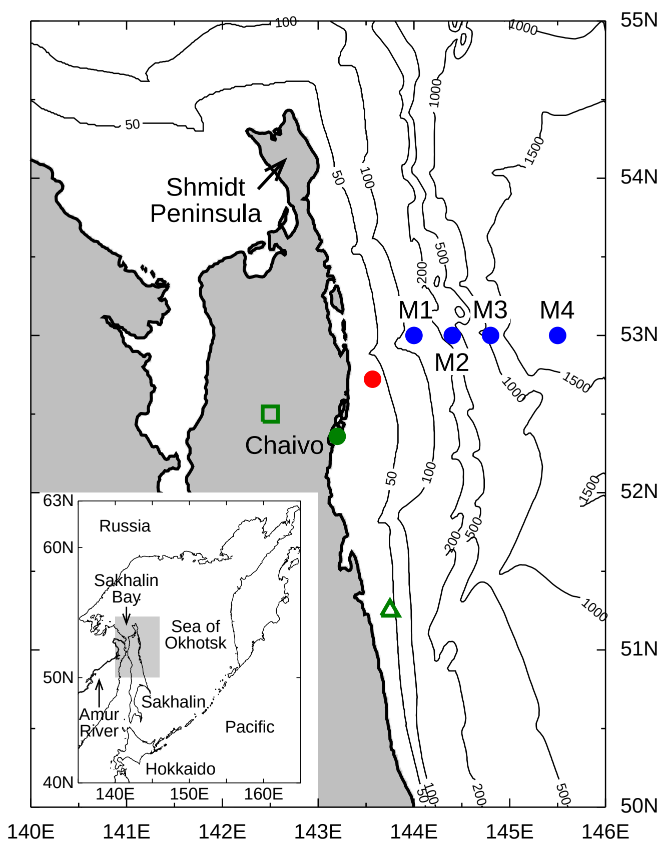

Fig. 1. Locations of the moorings (red circle) and Chaivo weather station (green circle). The square and triangle mark nearby ECMWF and ISCCP grid points, respectively. Blue circles mark moorings in 1998–2000. The inset shows the entire Okhotsk Sea wherein shading denotes the enlarged portion. Bathymetry from the General Bathymetric Chart of the Oceans.

3. Results

3.1. Wind, ice, and oceanic data

The wind data show that the northwesterly wind was dominant in winter and weakened in spring (Fig. 2a). The ice velocity data show that the meridional component was governed by the component of the wind velocity in the same direction, by diurnal tidal currents, and by the southward-flowing East Sakhalin Current, which attains a maximum in winter (Mizuta et al., 2003) (Fig. 2b). They also show that the zonal component corresponded well with the wind component (red in Figs. 2a and b). The draft data exhibits two distinctly different periods (Fig. 2c), those of thin-ice dominance in January–March only and those of thick-ice dominance throughout the duration. In Fig. 2c, horizontal bars at the top denote thin-ice periods, which are classified if the average draft including open water was less than 0.5 m over each 3-km-long draft section. All the data after 20 March are included in the thick-ice period because the heat loss was fairly small and thin ice was mostly absent. Note that the data on 17 February (Fig. 3a) and 21 March (Fig. 3b) correspond to these two periods, respectively. Comparison between the zonal ice velocity and draft data reveals that thin-(thick-)ice periods mostly occurred when ice velocity was directed offshore (onshore). (Here, the offshore and onshore directions are defined as eastward and westward.) In fact, 83% of draft values observed during thin-ice periods occurred when the zonal ice velocity was directed offshore. Therefore, the thin-ice periods are regarded as polynya periods. From the end of December to late February, salinity generally increased with occasional drops (red in Fig. 2d). Periods of salinity increase (drop) mostly corresponded with those of thin-(thick-)ice periods. In fact, 82% of the hourly salinity increase occurred during the thin-ice periods. These observations suggest that appreciable brine rejection was associated with ice formation in a coastal polynya around the mooring site during thin-ice periods. In fact, in situ temperature at 24-m depth was close to the freezing point with several supercooling events (blue below the lower horizontal line in Fig. 2e), which indicate active ice formation. Due to the near-freezing temperature (blue in Figs. 2d and e) and relatively high salinity caused by brine rejection (red in Fig. 2d), potential density exceeded a DSW threshold of 26.7 (the upper horizontal line in Fig. 2e) several times from January to March (red). This is the first observational evidence of the possible DSW formation off Sakhalin.

3.2. Brine rejection during polynya periods

During the thin-ice (polynya) periods, the data from the CT recorder (red in Fig. 2d) indicate active brine rejection associated with ice production. Here, we estimate ice production and concurrent brine rejection using heat-flux calculations. Following Ohshima et al. (2003), heat-flux calculations are performed at 1-s